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# CARBON DREDGE-UP IN LOW-MASS STARS AND SOLAR METALLICITY STARS

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## ABSTRACT

Results are presented for recent evolutionary calculations which show the third dredge-up to operate in stars with total masses as low as 1 $M_\odot$ without invoking any extramixing, such as overshooting. For 1.5 $M_\odot$ models dredge-up is obtained even for stars of solar metallicity. Many models became C stars of quite low luminosity. The dredge-up law operating in the models is discussed.

*Subject headings:* stars: carbon — stars: evolution — stars: late-type — stars: low-mass

The evolution of asymptotic giant branch (AGB) stars continues to present problems for stellar models. Since the discovery of the "carbon star mystery" (Iben 1981) many developments have possibly ameliorated the problem. For example, recent calculations by Lattanzio (1987*a*, *b*, 1989*a*) and Boothroyd and Sackmann (1988*a*, *b*, *c*, *d*) have succeeded in producing low-luminosity carbon stars, while calculations by Wood and Faulkner (1986) have shown the importance of envelope ejection via radiation pressure as a mechanism for explaining the scarcity (but not the total lack: see Wood, Bessell, and Fox 1983) of high-luminosity AGB stars. Certainly the situation is looking more hopeful.

Yet problems still remain. For example, the models of Lattanzio neglected mass loss which reduces the envelope mass as the star evolves along the AGB. Yet it is known that small envelope masses make dredge-up less likely (e.g., Wood 1981). Similarly, Boothroyd and Sackmann, although including (and probably overestimating) mass loss, may require (for some models) a larger value of $\alpha = l/H_p$, the mixing length to pressure scale height ratio, than is believed reasonable (see Lattanzio 1989*b* for a comparison of recent calculations).

Our current understanding is that only models with compositions appropriate to Population II stars exhibit dredge-up (see Wood 1981), yet carbon stars exist in the disk of our Galaxy (e.g., TW Hor; see Bouchet 1984). Likewise, the unambiguous overabundance of many *s*-process elements in AGB stars is unexplained at present. Models can produce *s*-process enhancements for core masses $\gtrsim 0.9\ M_\odot$ (Iben 1975, 1976, 1977), where the neutron source is $^{22}$Ne($\alpha$, $n$)$^{25}$Mg. Yet it is now well established that this is not the case for real stars, and the believed source of neutrons is $^{13}$C($\alpha$, $n$)$^{16}$O (e.g., Malaney 1987; Lambert 1989). But models exhibiting this neutron source fail to dredge the nuclear products into their envelope (Hollowell 1987), and some form of extramixing must be invoked (such as convective overshooting). Although a physically reasonable thing to do, the models then suffer from the uncertainty associated with calculating the extent of the overshoot. Also, in order to activate the $^{13}$C source requires, according to our present understanding, a semiconvective zone to form at the outer edge of the carbon pocket. Yet this does not occur in the models of Lattanzio and has a very small extent in the models of Boothroyd and Sackmann (again, see Lattanzio 1989*b* for a discussion). In any event, only models of low metallicity exhibit this semiconvection, whereas the *s*-process enhancements are seen in stars in the field, where we expect higher values of $Z$. (See Malaney 1989 and Lattanzio and Malaney 1989 for a possible alternative source of technetium in AGB stars.)

Clearly much work remains to be done, and much progress is yet to be made. There are two areas which warrant our immediate attention: the determination of the dredge-up law as a function of core and envelope mass and composition; and the interactions among pulsation, mass loss, and shell flashes. This *Letter* presents some recent results on the limits of dredge-up and is part of a program to investigate the composition dependence of the dredge-up law operating in 1.5 $M_\odot$ models. At present the models are constructed without mass loss and follow the techniques given in Lattanzio (1986). All models use $\alpha = 1.5$. Because previous calculations have shown that the helium abundance has a considerable effect on the quantitative results, I am considering $Y = 0.20$ and 0.30. In this *Letter* I report on calculations with $M = 1.5$, $Y = 0.20$, and $Z = 0.001$, 0.003, 0.006, 0.01, and 0.02. To investigate the dependence on envelope mass, I have also considered $M = 0.8$ and 1.0 for ($Y = 0.20$ and $Z = 0.001$). The $M = 0.8\ M_\odot$ model was constructed by artificially rescaling the mass coordinate, outside the core, of the 1.5 $M_\odot$ model during the "off" phase between the fifth and sixth pulses.

Table 1 lists the core masses at which carbon was first dredged into the stellar envelope, hereafter $M_{\rm H}^{\rm DU}$, for the various evolutionary sequences considered (the results for $Z = 0.003$ and 0.006 were briefly reported in Lattanzio 1987*b*). Also shown is the pulse number at which this occurred, $N_{\rm DU}$. If the model became a carbon star, then the next two columns give the pulse number at which C/O > 1 is reached, $N_{\rm C}$, and the bolometric luminosity at the bottom of the postflash dip following that pulse. We see that, for a given total mass, $M_{\rm H}^{\rm DU}$ increases with $Z$, but not so strongly that dredge-up is prohibited at solar metallicities, even for these low-mass stars. This is in quantitative disagreement with the simple envelope integrations of Wood (1981) and is clearly an important result, although somewhat tentative because of the neglect of mass loss. Nevertheless, the fact that dredge-up was also obtained in a 1 $M_\odot$ model (at $Z = 0.001$) indicates that the models have not yet reached the minimum (envelope) mass for carbon dredge-up.

Table 2 lists $\Delta M_{\rm dredge}$, the amount of hydrogen-exhausted material mixed into the envelope by convection, and the dredge-up parameter

$$\lambda = \frac{\Delta M_{\rm dredge}}{\Delta M_{\rm H}},$$

TABLE 1

Core Masses for Carbon Dredge-up and C/O > 1

| $M/M_{\odot}$ | $Z$ | $M_{H}^{DU}$ | $N_{DU}$ | $N_{C}$ | $M_{bol}$ |
|---|---|---|---|---|---|
| 1.0......... | 0.001 | 0.630 | 14 | 16 | −4.3 |
| 1.5......... | 0.001 | 0.605 | 7 | 9 | −4.0 |
| 1.5......... | 0.003 | 0.619 | 11 | 17 | −4.4 |
| 1.5......... | 0.006 | >0.62 | >13 | ... | ... |
| 1.5......... | 0.01 | 0.629 | 16 | 27 | −4.8 |
| 1.5......... | 0.02 | 0.635 | 21 | >30[a] | < −4.8[a] |

[a] Calculations were stopped following the 30th pulse when $M_{H} = 0.682\ M_{\odot}$ and C/0 = 0.694. At the present rate it is estimated that approximately another seven pulses would be required to produce a carbon star (neglecting mass loss).

TABLE 2

Dredge-up Parameters for the Sequences

| $N_{pulse}$ | $M_{H}$ | $\Delta M_{dredge}$ | $\lambda$ |
|---|---|---|---|
| $M = 1.0\ M_{\odot}, Z = 0.001$ | | | |
| 14......... | 0.6309 | 0.0006 | 0.075 |
| 15......... | 0.6380 | 0.0000 | 0.000 |
| 16......... | 0.6456 | 0.0010 | 0.134 |
| $M = 1.5\ M_{\odot}, Z = 0.001$ | | | |
| 7.......... | 0.6052 | 0.0001 | 0.136 |
| 8.......... | 0.6120 | 0.0022 | 0.292 |
| 9.......... | 0.6182 | 0.0035 | 0.417 |
| $M = 1.5\ M_{\odot}, Z = 0.003$ | | | |
| 11......... | 0.6257 | 0.0013 | 0.181 |
| 12......... | 0.6320 | 0.0002 | 0.026 |
| 13......... | 0.6388 | 0.0013 | 0.186 |
| 14......... | 0.6450 | 0.0013 | 0.173 |
| 15......... | ...[a] | ...[a] | ...[a] |
| 16......... | 0.6561 | 0.0027 | ...[a] |
| 17......... | 0.6609 | 0.0030 | 0.401 |
| $M = 1.5\ M_{\odot}, Z = 0.01$ | | | |
| 17......... | 0.6292 | 0.0007 | 0.103 |
| 18......... | 0.6353 | 0.0011 | 0.161 |
| 19......... | 0.6411 | 0.0000 | 0.000 |
| 20......... | 0.6476 | 0.0000 | 0.000 |
| 21......... | 0.6546 | 0.0000 | 0.000 |
| 22......... | 0.6603 | 0.0000 | 0.000 |
| 23......... | 0.6664 | 0.0016 | 0.261 |
| 24......... | 0.6714 | 0.0018 | 0.277 |
| 25......... | 0.6762 | 0.0020 | 0.303 |
| 26......... | 0.6808 | 0.0023 | 0.348 |
| 27......... | 0.6851 | 0.0025 | 0.378 |
| $M = 1.5\ M_{\odot}, Z = 0.02$ | | | |
| 21......... | 0.6352 | 0.0005 | 0.080 |
| 22......... | 0.6410 | 0.0010 | 0.159 |
| 23......... | 0.6464 | 0.0014 | 0.219 |
| 24......... | 0.6516 | 0.0000 | 0.000 |
| 25......... | 0.6576 | 0.0010 | 0.162 |
| 26......... | 0.6629 | 0.0013 | 0.214 |
| 27......... | 0.6678 | 0.0016 | 0.258 |
| 28......... | 0.6725 | 0.0016 | 0.250 |
| 29......... | 0.6771 | 0.0015 | 0.249 |
| 30......... | 0.6818 | 0.0018 | 0.297 |

[a] Data for pulse 15 lost.

where $\Delta M_{H}$ is the amount of matter processed by the hydrogen shell between pulses. We note that although $\lambda$ generally increases with each pulse, it is not uncommon for $\lambda$ to suddenly drop to zero for one or more pulses, especially near the commencement of the thermally pulsing evolution. No obvious parametrization of $\lambda$ suggests itself from these results: this will be addressed again when more calculations are completed.

Lattanzio (1986), using the results of Wood (1981), predicted that low-metallicity models would dredge carbon to their surfaces from virtually the first pulse. This was not seen in Lattanzio (1987*b*) and is due to the quantitative differences between the detailed calculations presented here and the simplified, exploratory calculations of Wood (1981). Although the variation found by Wood has been verified repeatedly, these models should not be used for quantitative studies.

The disk carbon star TW Hor was determined by Bouchet (1984) to have $L = 9000\ L_{\odot}$ and $T_{e} = 3250 \pm 200$ K. Assuming membership in NGC 1252 constrains the mass of the star: the turn-off mass of this cluster is about 2.2 $M_{\odot}$. At this mass, we expect little mass loss during the ascent of the first giant branch, and so this will be approximately the mass of stars commencing their thermally pulsing evolution also. The 1.5 $M_{\odot}$ models presented here have temperatures of 3300 K and 3100 K, for $Z = 0.01$ and 0.02, respectively, at $L = 9000\ L_{\odot}$. Either of these metallicities is appropriate to the disk population, and either temperature fits the value given by Bouchet. [The shift in log ($T_{e}$) associated with an increase in mass from 1.5 to 2.2 is about +0.02, while increasing $Y$ from 0.20 to 0.30 shifts log ($T_{e}$) by +0.01; Lattanzio 1986.] The observed $M_{bol}$ of −5.2 is again consistent with the minimum luminosity for carbon star characteristics at $Z = 0.01$ and $M = 1.5\ M_{\odot}$, and quite probably for $Z = 0.02$ as well (the higher mass will lower the critical luminosity [see Table 1], further improving the agreement). Certainly the present models provide a natural explanation for this, and probably any other, carbon stars of near-solar metallicity.

The $Z = 0.001$ model with $M = 0.8\ M_{\odot}$ has been followed through 28 pulses so far. Although coming extremely close, the convective envelope has not penetrated the hydrogen-exhausted region, and thus remains well short of the carbon-rich pocket. The core-mass following the 28th pulse is 0.746 $M_{\odot}$, and thus the envelope mass is only $\simeq 0.05\ M_{\odot}$. That no dredge-up has been seen for this mass composition is consistent with other calculations (e.g., Boothroyd and Sackmann 1988*d*; Hollowell 1987). It was found that the 1.0 $M_{\odot}$ model of this composition did experience dredge-up, so we can conclude that the threshold mass for dredge-up at ($Y$, $Z$) = (0.20, 0.001) is between 0.8 and 1.0 $M_{\odot}$.

None of the models presented in this study have shown the semiconvection noted by Iben and Renzini (1982) and Hollowell (1987), which appears to be a prerequisite for ignition of the $^{13}C$ neutron source. This is consistent with Iben and Renzini (1984) who find that the semiconvection only appears over a narrow region of the ($M$, $M_{H}$, $Z$) parameter space. Consequently the evolution of the 0.8 $M_{\odot}$ model will be continued in the hope of shedding some light on this mechanism.

Interestingly, after the 28th pulse, during what would be the dredge-up phase, a small convective region appeared at the hydrogen-helium interface at the base of the (now extinct) hydrogen shell. The size of this convective zone was $\sim 10^{-6}\ M_{\odot}$ and was of no practical consequence for the evolution of the model. There is also a second, larger convective zone ($\sim 10^{-5}\ M_{\odot}$) situated in the carbon pocket, well below the outer edge (i.e., the carbon-helium interface). Neither of these convective zones makes contact with regions of different chemical composition, with subsequent mixing of the abundances. The ratio $\nabla_{rad}/\nabla_{ad}$ at the outer edge of the carbon pocket remains less than 0.95 throughout the flash cycle (a value of unity would be needed to reproduce the semiconvection found by Iben and Renzini 1982 or Hollowell 1987). I have tightened the convergence criteria to one part in $10^4$, and altered the mesh spacing in the model, and yet these results do not change. The subsequent evolution of this model will be watched very carefully, and will be reported elsewhere.

The models presented in this *Letter* show that the previous belief that carbon dredge-up occurred only in models of low metallicity is not true. Indeed, the near-solar metal abundance cases become carbon stars at quite low luminosities. Two caveats must be mentioned: first, the models calculated so far (and presented in this *Letter*) use $Y = 0.20$, and second, they were constructed without mass loss. The $Y = 0.30$ cases are currently being investigated, but, based on previous calculations (e.g., Lattanzio 1986), we can expect the trends discussed in this *Letter* to apply also at $Y = 0.30$.

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